Chapter 12
Prescribed Burning for Regeneration

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Abstract

The character of most forest ecosystems in the southern U.S. has been shaped by fire. Indians and early settlers burned the woods for many purposes. After a period of trying to exclude fire, foresters recognized its value as an ecological force and its necessity as a management tool. This chapter describes the history of prescribed burning in the South, its effects on forest resources, and its use in regenerating the southern pines. Fires are prescribed before harvest to control small hardwoods that would compete with young pines of the next rotation and to prepare seedbeds for natural regeneration, and after harvest to reduce logging residues and again to control competing vegetation. Prescribed fires are also applied, for example, to improve habitat for certain wildlife species, to control disease, and to increase forage for grazing. Implementation of a prescribed-burning program and factors affecting fire behavior and influences are discussed. When properly applied, prescribed fire has many benefits and few adverse environmental effects. Although considerable information about prescribed burning has been accumulated over the decades, much remains to be learned to fine-tune the practice in an increasingly urban society.

12.1 Introduction

Prescribed burning – fire set under planned conditions to accomplish specific management objectives – is often used in the regeneration of southern pines. The successful mixing of fire and pine regeneration is not just a happy coincidence. Fire has always been an important ecological force helping to shape the structure and composition of the southern U.S. forest [28]. Indeed, the southern pines have adapted to a regime of periodic burning, not only tolerating it but requiring it (or the conditions created by it) for self-perpetuation.

This chapter discusses the use of prescribed fire in regenerating southern pines, environmental effects of prescribed fire, and factors affecting fire behavior and influences. Because prescribed burning is a valuable management tool from the standpoint of both versatility and cost, foresters need to be well acquainted with the benefits and liabilities of this practice.

12.2 History of Fire in the South

Before humans inhabited the Southeast 10 to 20 thousand years ago, lightning served as a mutagenic agent which forced species and communities to adapt to fire [28]. With the arrival of the early Indians, however, fire occurred more frequently. Indians were the first people in North America to practice what we now call "prescribed burning." They preferred the open grassland or savannah resulting from frequent burning – environments that provided access to grazers and browsers and to the wild grains, berries, and legumes that appeared after fire. Frequent (often annual) fires that reduced the growth of heavy underbrush ("rough") created the grassland and forests present when European settlers arrived.

European settlers, whose livelihood was often based on hunting and herding, quickly discovered the advantages of firing the southern woods. Exceptionally vigorous understory growth had to be controlled to provide abundant forage and browse. Frequent low-intensity burning kept the "rough" manageable, but did little to harm the pine and pine/hardwood overstory.

The logging industry migrated to the South from the Lake States just before the turn of the 20th century. Yet after a few decades of exploitive logging, most of the virgin pine forest had been cut, and fires set to consume logging residues, as well as those to improve grazing, prevented regeneration. Over 37 million hectares of cutover timberlands faced professional foresters when the last virgin pines were being cut [49]. It was obvious that control of random woodsburning was mandatory to allow the forests to regenerate.

The proper use of fire was much debated, but gradually experience and scientific evidence accumulated supporting the important role of fire in southern forest ecosystems. In the early 1900s, H. H. Chapman [7] of Yale University advocated the use of prescribed fire in longleaf pine (*Pinus palustris* Mill.) management. The wildlife biologist

M.L. Duryea & P.M. Dougherty (eds), Forest Regeneration Manual, pp. 235–250.

Stoddard [58] published a major study on bobwhite quail *(Colinus virginianus)* which showed the importance of prescribed fire in the management of this species. The consequences of a fire-exclusion policy were brought home by a series of disastrous wildfires which convinced many foresters of the need for prescribed fire to reduce fuel hazard and, therefore, wildfire damage. Today, many foresters recognize prescribed fire as an essential forest-management tool, but the general public has little understanding of its use and importance. Its benefits and liabilities are still being debated.

12.3 Implementing a Prescribed-Burning Program

Prescribed burning is widely used today but, because of its potential hazards, should be conducted only by well-trained experienced personnel. Each burn is affected by a unique set of stand, fuel, and weather conditions and, therefore, requires extensive planning. Because of the numerous variables that affect prescribed burns, only a general outline for planning prescribed burns summarized from Brown and Davis [5] and Mobley et al. [41] can be presented here.

12.3.1 The Prescription Process

A clear description of management objectives is a prerequisite for all other steps in planning a burn. Both primary and secondary objectives should be stated. If, for example, the primary objective is to provide browse for white-tailed deer (*Odocoileus virginianus*) and the secondary objective is to control understory hardwoods, several burns at intervals of 2 to 6 years may be prescribed. If the primary objective is site conversion from hardwood to pine, a hot broadcast burn during summer would be prescribed to reduce logging residues and improve plantability of the site. The statement of objectives should also indicate the specifics of the desired outcome (for example, how much vegetation should be killed or consumed) and fire intensity. This information may allow managers to choose among several firing methods that will provide the same results (see 12.6.2).

A written description of the burn unit should include its location and size, its fire history, and a complete description of the overstory, understory, fuels, soil type, and topography. Units should be small enough to be burned completely under one set of burning conditions, usually within a day. A unit's actual size may vary from less than one to several hundred hectares depending on management objectives, firing method, laws and regulations, and available personnel. A detailed map should show the boundaries of the unit, indicating the presence of natural or artificial fire breaks. The map should also show land ownership, topography, placement of fire lines, areas that should not be burned, potential escape routes, and a diagram of the firing method. Potentially hazardous areas within the burn unit, such as those with heavy fuel accumulation, should be indicated on the map, as should special cases such as scenic areas, streamsides, archaeological sites, and cemeteries. Whenever possible, selected boundaries should take advantage of natural fire breaks such as swamps and ridges or artificial fire breaks such as roads, skid trails, and power lines.

Where fire breaks do not already exist, fire lines should be established, usually by plowing before burning and as close to the burn date as possible to minimize litterfall in the lines. To reduce erosion, fire lines should be shallow and on the contour in hilly terrain. Water bars should be constructed on steeper fire lines. Lines should be as straight as practical, and sharp corners should be avoided; brush and snags near the boundaries or left within lines should be removed. An extra precaution around hazardous areas is to plow parallel lines and burn the area between them before igniting the entire unit. Additional fire lines within the boundaries of burn units are required for some firing methods.

A burning prescription should state the year and season of burning, and the weather and fuel conditions under which the burn will be conducted. Selection of the best year to burn depends on vegetation size and management objectives. Burning every year, for example, provides a high degree of protection but is usually impractical because of limited fuel buildup. In the Southeast, areas are commonly burned every 2 to 4 years to reduce fuel buildup; this period allows sufficient accumulation to support burning without significantly increasing the danger to overstory trees.

The season of burning is related to fire intensity and the stage of vegetative development that will best suit management objectives. Winter burns are common for reducing wildfire hazard and controlling understory vegetation. These burns typically are cool and cause little damage to overstory trees. Spring burns are difficult to conduct because of variable weather conditions and interference with wildlife breeding seasons. However, they effectively kill small vegetation which is rapidly growing and highly susceptible to fire damage. Summer burns are most effective at killing competing vegetation, reducing fuel buildup, and preparing seedbeds and sites for planting. However, they pose the highest risk to overstory trees when present.

Selection of the specific day to burn can be the most difficult step in fire planning because numerous weather and fuel conditions must be considered. Because of the large number of variables involved, relatively few days each year are optimal for prescribed burning, and managers may be tempted to burn on marginal days when management objectives may not be satisfied. Several prescriptions that will achieve the desired results for days with different weather conditions should be developed.

Accurate weather forecasts on the day of burning are essential. The range of acceptable weather conditions is generally so narrow that burning can be conducted only during a portion of the day. In the Southeast, acceptable weather conditions for understory burning most commonly occur in the winter, 1 to 3 days after a cold front passes. The cold front is typically accompanied by rainfall and is followed by steady northwesterly winds, low temperatures, and low relative humidity. Logging residues are generally broadcast burned in the summer. The presence of cured fuels resulting from herbicide application or felling of unmerchantable trees left after logging allows burning soon after a soaking rain.

The choice of firing method is determined by the desired fire intensity. Head fires (those that travel with the wind or upslope) produce high temperatures and tall flames. These burns are effective where fuel loading (the total amount of material available for combustion at a given time) is low or for site preparation where there is no overstory to protect. Backing fires (those that travel against the wind or downslope) produce relatively cool temperatures and short flames; although safer than head fires, backing fires are more expensive because they move slowly. Several firing methods combine the effects of head and backing fires (see 12.6.2). An experienced fire manager must select a firing method for a given set of objectives and conditions but remain flexible, changing the technique as necessary to allow for unexpected stand, fuel, or weather conditions.

Managers should evaluate fire effects soon after burning to determine whether the fire achieved the stated objectives and, if not, what additional steps are necessary. If a second burn is required, the entire planning process should be repeated. Damage to the timber stand should also be considered. Most southern pines will survive what appears to the untrained eye as excessive damage. However, growth rates may be severely reduced. On the basis of the degree of stand damage, the manager must judge whether to salvage damaged trees, harvest the entire stand and regenerate, or do nothing. With well-planned and -executed prescribed burns, damage is seldom severe enough to require timber harvest.

12.3.2 Local, State, and Federal Laws

Before beginning a prescribed burn, the fire manager should be familiar not only with the technical aspects of the practice, but also with the laws and regulations governing fire use to avoid possible criminal charges or lawsuits. Fire can destroy property or cause injuries, and smoke can be a health or safety hazard. Laws regulating prescription burning in the South discussed by Hauenstein and Siegel [23] and Siegel [57] are summarized here. However, state forestry agencies should be contacted to determine the current local laws which apply to prescribed burning.

Most laws concerning prescribed burning deal with the control of air quality or prevention of wildfire. Effects of prescribed fire on air quality are governed mainly by the Clean Air Act of 1970 (PL 91–601) and major amendments in 1977 (PL 95–95). Although the impact of these laws on prescribed burning is somewhat uncertain at present, the general trend is to allow individual states to establish smoke-management guidelines (see 12.3.3).

Most southern states require a written permit or at least some form of notification of the intent to burn that will forewarn fire-suppression organizations such as state forestry agencies or local fire departments. Many states have established specific restrictions to prescribed burning: several prohibit burning within a certain distance of specified land-use areas (such as residential or recreation sites), some restrict burning to daylight hours to limit visibility problems, and yet others restrict burning during some portion of the year (particularly during the fire season). Almost all southern states prohibit burning during droughts.

Laws also exist concerning civil liability for personal injury and property damage. Any person conducting a prescribed burn can be found liable if damages result from the fire itself or the smoke it produces, regardless of whether a law has been broken. Generally, the injured party must prove negligence in either starting the fire or controlling it. In several states, the landowner is liable to the fire-suppression organization for fire-fighting costs when a prescribed fire escapes.

12.3.3 Smoke-Management Guidelines

The practice of prescribed burning includes the responsibility of wise use, land stewardship, and being a good neighbor. Each user has an obligation to minimize adverse environmental impacts. Although research on smoke management is relatively new, guidelines are now available in the *Southern Forestry Smoke Management Guidebook* [64]. Smoke management is also discussed by Mobley et al. [41] and Mobley [40]. A brief introduction to smoke management is presented here, but managers should be thoroughly familiar with the *Guidebook* before conducting any burn.

Currently, most southern states have voluntary smoke-management guidelines which are intended to be useful without being excessively restrictive. A few states restrict the issuing of burning permits during periods of high air stagnation, and most restrict the use of rubber tires, asphalt, and other hazardous smoke-producing agents for starting fires. Many states have rules which address the amount of soil in burned windrows, prevention of smoke hazards near roads, airports, and residential areas, and curtailment of burning when air is heavily polluted.

Objectives for prescribed burning should be compatible with air-quality laws and regulations and should consider both on- and off-site environmental impacts. Plans should be made to notify fire-suppression organizations, nearby residents or businesses, and adjacent landowners of the intent to burn. Should wind direction change, burning crews must be prepared to control traffic on affected highways and extinguish the fire, if necessary. A system described by the *Guidebook,* [64] which is available for several types of computers, aids managers in the planning process by identifying smoke-sensitive areas and critical targets, determining the effects of smoke from various types of fuel, and suggesting steps to minimize the risk of adverse effects.

The impact of smoke can be reduced by burning under proper weather conditions. The fire manager should have current weather forecasts with enough information to predict smoke behavior. Both surface weather and upper atmospheric conditions are important. Burning should be conducted when wind is moving away from sensitive areas such as highways and homes. The atmosphere should be slightly unstable for optimum smoke dispersal without loss of control of the fire. Burning at night should be avoided because visibility is poor and because weather and smoke behavior are more difficult to predict.

On the day of the burn, the fire manager should check with pollution-control agencies about pollution alerts or temperature inversions. If none exist, a small test fire should be set to determine the direction and behavior of smoke. Areas next to roads should be burned quickly and when road use is low; mopup (the work required to completely extinguish all fire) should follow as soon as possible to reduce smoke hazard. Where possible, burning should be conducted in small blocks and with backing fires to minimize the volume of smoke produced.

12.4 Burning to Enhance Regeneration

12.4.1 Understory Burning

Understory burning in southern pine stands accomplishes numerous forest-management objectives. Most of the prescribed burning in the South is done to reduce fuel buildup, but much of it is done to improve wildlife habitat and grazing. However, in this section, we limit our discussion to burning to enhance regeneration of southern pines.

12.4.1.1 Controlling understory hardwoods

The effectiveness of pine regeneration is greatly enhanced and the expense of site preparation reduced if the hardwood trees of the previous stand were controlled by frequent understory burning. Otherwise, these hardwoods, which compete intensely with establishing pine seedlings, must be controlled with expensive mechanical and/or chemical treatments.

Long-term research has shown that periodic burning controls the size [diameter at breast height 1.37 m above ground (dbh and height], not the number, of hardwood stems in pine stands (Figs. 12.1, 12.2). The degree of control depends upon the intensity, frequency, and season of burning [30, 34], as well as upon overstory stand density and site quality. Low-intensity prescribed fires in pine stands are not effective in killing hardwood stems > 5 cm in diameter [18], so understories must be burned frequently enough (generally every 2 to 6 years) to prevent stems from

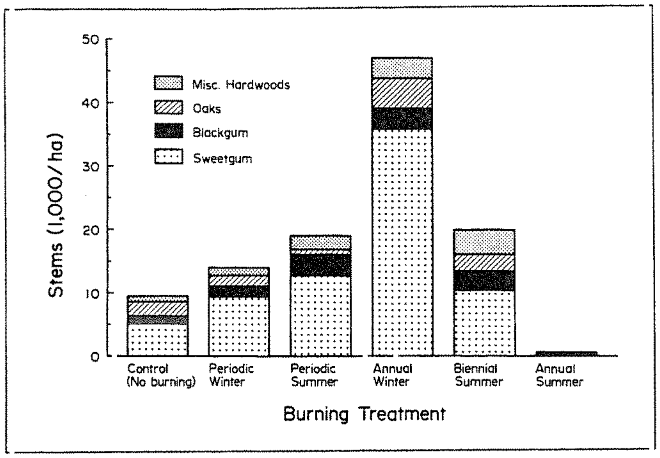

Figure 12.1. Number of understory hardwoods < 2.5 cm dbh after 30 years of prescribed burning, by treatment, for various species including oaks (*Quercus spp.*), blackgum (*Nyssa sylvatica* Marsh.), and sweetgum (*Liquidambar styraciflua* L.) [30].

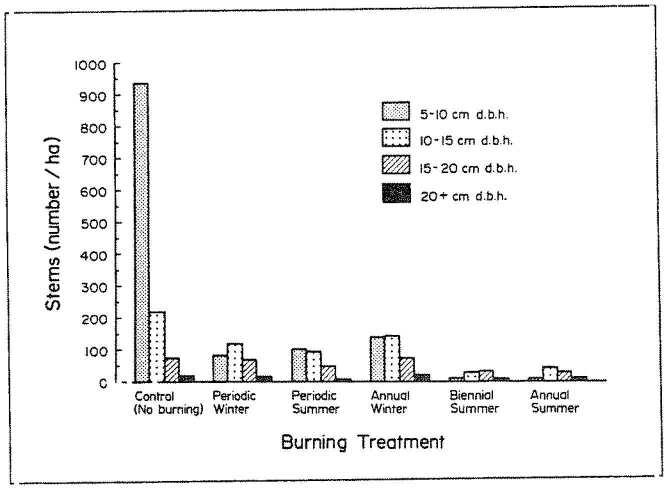

Figure 12.2. Diameter distributions of all understory hardwoods > 5 cm dbh after 30 years of prescribed burning, by treatment [73].

reaching this size.

Spring and summer burns are more effective in top-killing (mortality of the stem and crown) hardwoods than dormant-season fires [4, 18, 30]. The vigor of new sprouts, which generally arise from the root collar of top-killed hardwoods or from root suckers in certain species, is greater following dormant-season burns. However, spring burning is usually avoided because it conflicts with the breeding season of many wildlife species.

Understory hardwoods, though extremely tenacious, can be eliminated by repeated annual summer burning; 3 to 10 annual burns will eliminate 80% of the rootstocks, depending on species (Fig. 12.3a). Burning every other summer is much less effective (Fig. 12.3b), killing generally < 50% of the rootstocks over a period of 26 years. Biennial summer burning gradually increases the oak

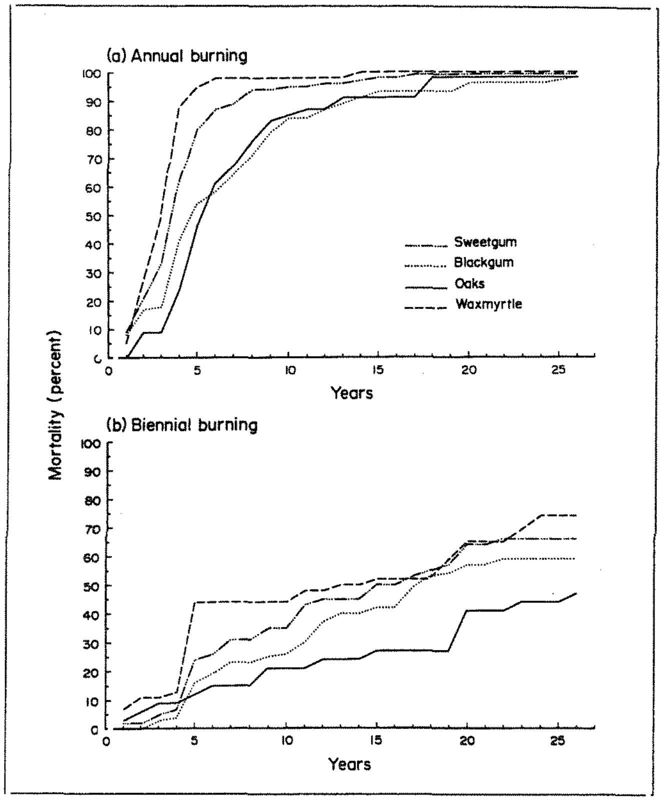

Figure 12.3. Cumulative mortality of hardwood rootstocks over 26 years of annual (a) and biennial (b) summer burning for sweetgum, blackgum, oaks, and waxmyrtle (*Myrica* spp.) [30].

component because other associated species are more susceptible to fire-caused mortality. Annual winter burning, even if done for decades, will not kill hardwood rootstocks [30]. Occasional burning often increases the per-area density of hardwood stems because multiple sprouts arise from single top-killed stems. Moreover, hardwood species composition is unlikely to be changed by burning rotations of 4 to 6 years because no hardwood species are eliminated and all sprout.

12.4.1.2 Enhancing natural regeneration

The southern pines can be regenerated with any of the classical natural regeneration methods (see chapter 3, this volume). Prescribed fire may be used for seedbed preparation in most cases with these methods either before or after logging, depending on the time of harvest. If logging is scheduled for the dormant season, the seedbed should be burned late the previous summer [76]. A series of burns beginning 2 to 3 years before harvest will be necessary if understory hardwoods and fuel buildup are serious problems. The first burn should be a cool winter burn to reduce fuel loading; subsequent summer fires provide additional hardwood control and seedbed preparation.

Preharvest burns are normally of low intensity (flame lengths < 1 m). Even though most low-intensity fires do not expose mineral soil, a burned seedbed is usually adequate. A study in the Coastal Plain of North Carolina [76] showed that an average of 9 sound seeds were required to establish 1 seedling on a mechanically disturbed, mineral soil seedbed, whereas 15 seeds were needed on a burned seedbed and over 40 seeds on an unburned seedbed.

Preharvest burns have been used to prepare seedbeds for most of the traditional natural-regeneration methods. Burning is recommended before the reproduction cut of the seedtree and shelterwood methods for loblolly pine (*P. taeda* L.) [2], slash pine (*P. elliottii* Engelm.) [56], and shortleaf pine (*P. echinata* Mill.) [31]. Low-intensity burns have also been effectively used to regenerate loblolly pine in the Coastal Plain [35] and Piedmont [68] by clearcutting with seed and/or seedlings in place. Many natural pine stands have become established following clearcutting when seed from adjacent stands fell on burned seedbeds.

If logging is scheduled for spring or summer, it may be best to delay burning until after harvest. A preharvest burn at this time would destroy recently germinated pine seedlings and give hardwood sprouts a year's growth advantage over pine seedlings that become established the next spring. A post-harvest burn in late summer prepares a good seedbed and allows pine seedlings and hardwood sprouts to begin growth on a more equal basis. Care must be taken to prevent damage or mortality of residual seedtrees or shelterwood trees when burning follows spring or summer harvests.

Fire is often used with other treatments to prepare seedbeds. Hardwoods > 5 cm in diameter are not consistently killed by low-intensity fire and may need to be treated with herbicides before or after burning (see chapter 13, this volume). Seedbeds are often chopped before burning when logging is conducted in spring and summer; chopping reduces the vertical component of fuels and allows burns to be conducted with fewer flare-ups, which could damage seedtrees.

12.4.1.3 Special considerations for different pine species

Loblolly pine seedlings are readily killed by fire. The South Florida variety of slash pine (var. *densa* Little and Dorman) is more fire resistant than is the typical variety (var. *elliottii*) because the former sprouts from buds near the root collar when tops have been killed by fire. Shortleaf, pond (*P. serotina* Michx.), and pitch pine (*P. rigida* Mill.) seedlings also sprout from dormant buds [29]. Because seedlings are either killed outright or set back by fire during their early years, however, prescribed burning is not recommended for most pine species until they are at least 3 to 4 m tall.

Longleaf pine can tolerate, and often requires, frequent fires when in the grass stage to control brown-spot needle blight (*Scirrhia acicola*). Once root-collar diameters exceed 1 cm, longleaf pine seedlings resist fire damage. Winter burning is recommended if surveys of crop seedlings indicate 20% or more of their foliage is infected with the disease [3]. Frequent burning also reduces hardwood competition which, along with disease control, hastens growth of longleaf pine seedlings out of the grass stage. Because of its ability to withstand frequent burning when in the seedling stage, longleaf pine is better adapted than other species to the use of prescribed fire in uneven-aged management [3].

Prescribed fire can easily destroy stands of thin-barked species such as Virginia (*P. virginiana* Mill.), sand [*P. clausa* (Chapm. ex Engelm.) Vasey ex Sarg.], and white (*P. strobus* L) pine. Therefore, the preharvest use of fire to prepare seedbeds for these species is limited at best. However, because of its typically sparse understory, the Choctawhatchee race of sand pine (var. immuginata) can be burned under proper weather and fuel conditions [46]. White pine, which is adapted to cool northern aspects in the southern Appalachians, is especially sensitive to overly intense burns. Indeed, fires which consume all the litter and duff may adversely affect long-term site productivity of all species.

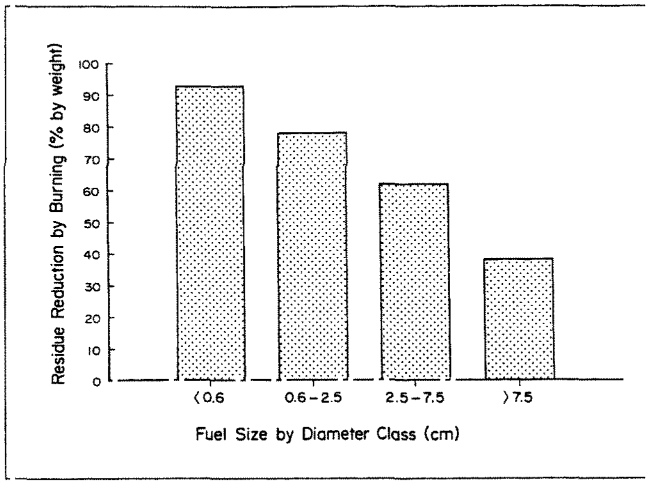

Figure 12.4. Percent reduction by weight of logging residues, by fuel diameter class, after burning [52].

12.4.2 Site-Preparation Burning

For successful regeneration of southern pines, some form of site preparation generally is required after clearcutting to decrease the amounts of logging residues and control competing vegetation. Logging residues cast shade on seedlings, occupy space where pines could be growing, and make planting more difficult and expensive. Phillips and Van Lear [48] reported that logging residues averaged 67 Mg/ha from bottomland hardwood stands, 20 Mg/ha from natural pine stands, and 7 Mg/ha from pine plantations. Fuel loads of up to 157 Mg/ha, including litter, duff, live vegetation, and slash, have been reported in the southern Appalachians [52].

Two methods of prescribed burning are used for site preparation in the South. Broadcast burning refers to the burning of logging residues as they lie in place (see 12.4.2.1). Pile and windrow burning ("pile and burn") generally refers to the use of heavy machinery to push logging residues into piles or windrows before burning (see 12.4.2.2). Burning of residues results in moderate-intensity (0.5 to 2 million $J.sec^{1}.m$) to high-intensity (2 to 4+ million $J.sec^{1}.m$) fires; fire intensity is greater than with understory or preharvest burning because of firing methods and high fuel loadings.

12.4.2.1 Broadcast burning

Broadcast burning is generally conducted in summer or early autumn following harvest, in combination with chemicals or alone. Herbicides are often used to kill herbs and shrubs that regrow after harvest but before burning (see chapter 13, this volume) with the technique popularly called "brown and burn." Application of herbicides allows burning sooner after a rain when site damage would be less likely; moreover, herbicides prevent hardwood sprouting.

A technique which does not use herbicides has been developed and tested in the southern Appalachians [1]. Residual trees left after harvest of hardwood or mixed pine-hardwood stands are felled in spring after leaves are nearly fully developed, allowed to cure for about 2 months, and burned in early to mid-summer when sprouting vigor of hardwoods is lowest [18, 78]. Pines are planted the following winter. This technique allows sites to be burned within days of soaking rains when duff and soil are moist.

The general goal of broadcast burning is to improve planting conditions by reducing logging residues. However, at the same time site quality must be protected. These seemingly conflicting goals can best be reconciled by burning under the proper fuel and weather conditions. In the presence of cured fuels, burning within a few days of a soaking rain removes over 90% of the fuel particles < 0.6 cm in diameter (Fig. 12.4] but only 39% of those > 8 cm [52]. Consumption of the smaller particles allows for an easier and, therefore, better job of hand planting. On the Andrew Pickens Ranger District in South Carolina, pine seedling survival has consistently exceeded 90% with hand planting after broadcast burning [47]. If the site is to be machine planted, a V-blade in front of the tractor pulling the planting machine can easily displace larger fuel particles (see chapter 17, this volume).

Broadcast burning offers several advantages over pile and burn. Because heavy equipment is not required, the technique is less expensive, soil compaction is reduced, forest floor and topsoil are less disturbed, and steeper sites can be prepared for regeneration. After burning, some large debris and part of the forest floor remain; their presence reduces erosion and returns nutrients to the soil. The herbs that germinate quickly after broadcast burning also help prevent erosion and improve wildlife habitat. Broadcast burning can be conducted more quickly than pile and burn, which reduces costs and decreases smoke-management problems. Although most firing methods can be used, aerial ignition is increasingly preferred because it allows for much faster ignition of multiple units under near ideal weather, fuel, and smoke-dispersal conditions.

12.4.2.2 Pile and windrow burning

On about one-third of the land burned for site preparation by industry, logging residues are pushed into piles or windrows and burned at a later date. This pile and burn technique removes more logging residue from the site than does broadcast burning and provides greater control of competing vegetation. In areas where machine planting is desired, pile and burn is preferable because broadcast burning usually will not remove the larger debris; it may also be preferable where logging residues are too light and scattered to support a broadcast burn.

When slash is pushed into piles, care must be taken not to disturb the forest floor and mineral soil. In many cases, much of the humus, top soil, and associated nutrients are displaced into piles and windrows, degrading site quality [6, 43]. Further, including soil in burn piles and windrows causes them to smolder for long periods. Without the convection updraft from an active flaming front, smoke from this glowing combustion phase may linger near ground level for days or weeks, polluting the air.

12.5 Environmental Effects of Prescribed Burning

12.5.1 Vegetation

Most southern pines larger than sapling size can tolerate a relatively high degree of crown scorch, especially during the dormant season, with minimum effects on survival and growth [29]. Even during summer and early fall, pole-size loblolly pine can generally tolerate all but complete scorching of foliage and still recover. Lower crown classes are more susceptible to fire-induced mortality than are dominant and codominant trees [72]. Smaller trees are more sensitive and are especially vulnerable to crown scorch during spring, when leaders are succulent. Severe crown scorch usually results in both diameter- and height-growth losses [29]. Length of the first flush following burning is most affected, with subsequent flushes often showing little adverse impact [71]. However, some managers consider growth loss due to scorch as the price of insurance against wildfire damage.

Hardwoods are not generally as resistant to fire damage as conifers, primarily because of their thinner bark. However, some hardwoods develop exceptional bark thickness upon maturity. Yellow-poplar (*Liriodendron tulipifera* L.) has long been recognized as one of the most fire-resistant species in the East when its bark thickness exceeds 1.3 cm [45].

Hardwoods have developed another adaptation-sprouting-to ensure their survival in ecosystems where fire is periodic. Suppressed buds at or below ground level often survive the heat of a surface fire, and sprout in response to the loss of apical dominance. Generally, many sprouts arise from a stump but are thinned over time to one or a few per stump.

The evolution of light, wind-disseminated seed by many hardwood and pine species is probably an adaptation to frequent burning. These light-seeded species often pioneer on burned seedbeds. Some species, yellow-poplar for example, produce seed that remain viable in the duff for years. Yellow-poplar seed stored in the lower duff germinates rapidly following winter prescribed fires [54].

Herbaceous vegetation thrives on burned seedbeds. Legumes are abundant in young loblolly pine plantations in the Georgia and Virginia Piedmont where logging residues are burned [11]. However, single low-intensity prescribed fires in older, unthinned pine stands are not likely to stimulate production of herbaceous plants, because either mineral soil is not exposed or light is limiting to germination or growth.

Community structure is altered by burning, e.g., a shrub layer may be completely eliminated and replaced by a grass and forb layer if burning is frequent [30]. The absence of fire will favor more shade-tolerant, less fire-tolerant species, and succession will proceed toward a climax, rather than a fire-maintained subclimax, community type.

12.5.2 Soil and Water

The interaction of many factors determines the effects of fire on soil and water [62, 75]. Most evidence indicates that low-intensity prescribed fires have few, if any, adverse effects on soil and water properties and may increase soil fertility. Low-intensity flames (< 1 m flame length) normally consume less than half the forest floor [4, 27], leaving mineral soil exposed in only small isolated patches even when burning is repeated over several years [39, 42]. When a portion of the forest floor remains and the fine root mat is intact, mineral soil is protected and soil physical properties are unaltered.

Soil erosion is generally not increased in relatively steep terrain when either low- or high-intensity burns are conducted under proper fuel and weather conditions. Soil losses following single prescribed burns in the Piedmont have been minimal [4, 12]. A high-intensity broadcast burn in the southern Appalachians conducted soon after a soaking rain did not increase soil movement on slopes of up to 43% [67]. The presence of residual duff and root mat maintain favorable hydrologic conditions on properly burned areas and minimize erosion. In addition, shrubs and herbs often regrow more rapidly on burned areas, with obvious advantages for erosion control and wildlife habitat. In contrast, Ursic [63] found that sediment levels on burned watersheds were several-fold greater than those on unburned plots, although sediment output was only about 1.1 Mg/ha.

Effects of prescribed fire on soil fertility are difficult to predict. Long-term studies (Fig. 12.5a,b) have shown that levels of organic matter and total nitrogen (N) are higher in the mineral soil on annually burned Coastal Plain plots, probably because of greater abundance of herbs and N-fixing legumes [37]. Levels of available phosphorus and

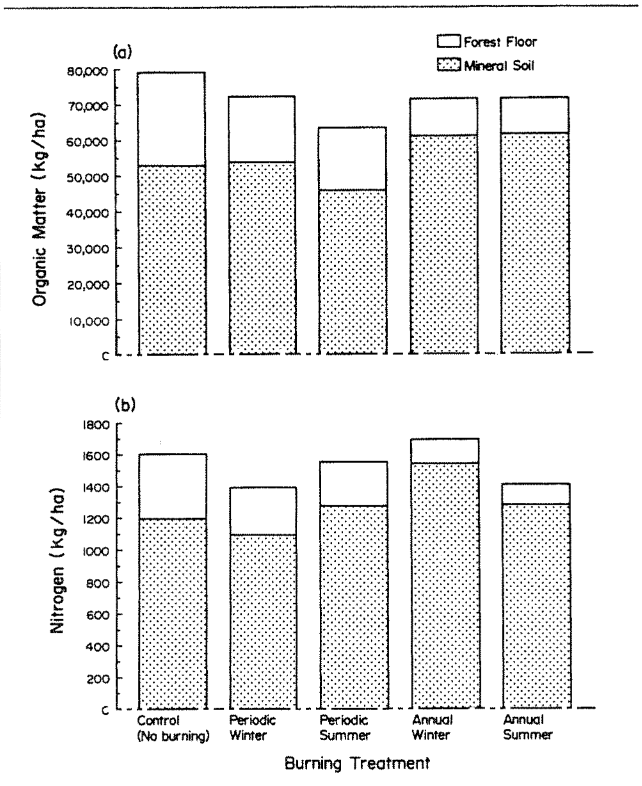

Figure 12.5. Levels of organic matter (a) and total nitrogen (b) in the forest floor and mineral soil (0- to 10-cm depth) after 30 years of prescribed burning [37].

calcium also are higher in mineral soil on those burned plots.

Effects of prescribed burning on soil N vary. Nitrogen availability increased following burning in a mature loblolly pine forest in the Piedmont of North Carolina [53]. However, long-term burning in an oak-hickory stand reduced available nitrogen [66], apparently due to an adverse effect on substrate quality.

Nitrogen losses generally result from volatilization during burning. Amounts of nitrogen in southern forest soils vary widely, but probably average about 2,200 kg/ha [14], most of which is unavailable to plants. Nitrogen volatilization during low-intensity burning in loblolly pine ranges between 22 kg/ha [27] and 112 kg/ha [74]. High-intensity fires used to reduce amounts of logging residues volatilize larger quantities of N. However, nitrogen is continually being added to southern ecosystems via processes such as nitrogen fixation and wet and dry deposition. Jorgensen and Wells [26] and Van Lear et al. [69] showed that 1 to 4 kg/ha of N were added annually to the site via nonsymbiotic N fixation in undisturbed pine stands in the Piedmont. Jorgensen and Wells [26] found that nonsymbiotic N-fixation rates increased from about 1 to 26 kg/ha annually when poorly drained Coastal Plain soils were burned. Nitrogen inputs from precipitation approximating 6 kg/ha annually have been measured in the southern Appalachians [61] and in the upper Piedmont [69]. Because the quantities of nutrients lost depend on the intensity and frequency of burning, managers should consider burning programs in which inputs balance outputs for the most critical nutrient on that site.

Prescribed fire can affect water quality by increasing sedimentation and, to a lesser degree, dissolved salts in streamflow [62]. However, most studies in the South indicate that effects on water quality are relatively minor and temporary. Douglass and Van Lear [16] found that two low-intensity burns before harvest had no effect on nutrient or sediment concentrations in ephemeral streams in the Piedmont of South Carolina. Richter et al. [50] failed to detect any major impact of prescribed fire on soil-solution nutrient levels in the Coastal Plain.

12.5.3 Air Quality

Smoke management – i.e., planning and executing burns so that smoke is rapidly dispersed into the atmosphere and away from sensitive areas – may hold the key to continued burning in the Southeast [70]. Unless adequate precautions are taken to protect sensitive areas, prescribed burning will become more restricted (see 12.3.3).

Particulates, which are complex mixtures of soot, tars, and volatile organic substances, either solid or liquid, are the major pollutant in smoke [15, 19, 51]. Large particles (50 to 100 μm in diameter) normally drop out near the fire and cause few problems. However, most of the particles formed in forest fires are of submicron (0.1 to 0.5 μm) size, typical of a combustion aerosol [38]. Under certain atmospheric conditions (low wind speeds and high humidity), small particulates serve as condensation nuclei resulting in dense smoke or combinations of smoke and fog. Reduced visibility during and after prescribed fires has caused numerous highway accidents.

Smoke often accumulates in depressions or along stream channels and other low-lying areas. When the relative humidity approaches 90%, which is common at night, fog formation is stimulated by the presence of smoke. The combined effect on visibility of smoke and fog is far greater than that of smoke alone. Even smoke from a smoldering fire several days old can seriously impair visibility far from its origin under certain atmospheric conditions.

In addition to particulates, carbon dioxide, water vapor, gaseous hydrocarbons, carbon monoxide, and nitrous oxides are released from fire [8]. However, only a small proportion (< 3%) of the total national emissions of particulates, carbon monoxide, and hydrocarbons can be attributed to prescribed burning.

12.5.4 Wildlife Habitat

Wildlife habitat can be improved or degraded by prescribed fire as numerous studies and several bibliographies and symposia have shown [21, 22, 36, 77]. Prescribed fire can improve habitat of many game species by increasing sprouting of browse (woody plants), providing seedbeds for legumes and herbs, stimulating germination of seed stored in the forest floor, and setting back succession to create or maintain cover. However, prescribed fire can degrade habitat of certain wildlife species by destroying nesting sites and cavity trees and simplifying community structure (see chapters 21 and 22, this volume). Knowing the habitat requirements of species to be managed, particularly those of threatened or endangered species, will allow fire to be used or prohibited as appropriate.

Just as plants and plant communities in the South have adapted to frequent burning, so have the resident animals. Effects of fire on the habitat of the white-tailed deer and bobwhite quail have received the most study. Increased sprouting of hardwoods and other browse after fire has been well documented [32, 34, 60]. Burning generally increases protein, phosphorus, and calcium contents of browse, as well as enhances its palatibility, although these effects are often short lived. In addition, periodic winter and summer burns temporarily increase numbers of woody plants, forbs, grasses, and legumes. Forage yields in Florida were higher after spring than fall and winter burns [33]. Repeated annual summer burns destroy rootstocks of most browse, thus eliminating understory mast-producing plants and allowing sites to be dominated by fire-tolerant forbs and grasses.

Although most burning regimes increase sprouting, they may temporarily decrease fruit production. Fruit production of gallberry (*Ilex* spp.), huckleberry (*Gaylussacia* spp.), and blueberry (*Vaccinium* spp.) was reduced the first year after prescribed burning in 16- to 30-year-old slash pine plantations in Georgia, but markedly increased by the third year [25]. In Florida, fruiting of gallberry plants was set back the first year by fire, but was heavy the second year [24]. Fruit production of woody shrubs did not differ on burned and unburned pine plantations in east Texas 3 years after burning [59]; moreover, dogwood (*Cornus* spp.) fruiting was increased by winter burning under dense pine-hardwood overstories.

The increase in abundance and seed production of legumes following fire is well documented [9, 13, 58]. Stoddard's classic study [58] showed that populations of bobwhite quail could not be maintained without regular annual burning. Nearly all the legumes (93 species) and grasses (59 species) used by quail thrive in fire-maintained savannahs. Insects, which are an important part of the quail's diet, also prefer open grasslands created by frequent burning [28].

The red-cockaded woodpecker (*Picoides borealis*), an endangered species, generally nests in open, parklike stands of pine with sparse midstories. Prescribed burning is recommended in old-growth pine stands to provide potential nesting habitat by controlling the density and height of the hardwood understory [65]. Conner [10] discussed effects of prescribed fire on snags and cavity trees. Although burning may destroy snags, which are easily ignited, it may also create snags by killing other standing trees.

Deer, turkey (*Meleagris gallopavo*), and quail are three major game species favored by the relatively open pine stands and improved browse created by periodic burning. They apparently are favored by broadcast burning to remove logging residues, as well. However, some wildlife species may be disadvantaged or actually hurt by regular use of fire. More research is needed to determine the requirements of nongame species before fire can considered in managing their habitat [77]. (For more information on wildlife interactions, see Chapters 21 and 22, this volume.)

12.6 Factors Affecting Fire Behavior and Influences

The success or failure of any prescribed burn is largely determined by fire behavior. In a mature pine stand, for example, a slow-moving low- intensity fire may be satisfactory for reducing hazards or preparing the seedbed, whereas a high-intensity fire may cause severe damage to overstory trees. A fire manager must be able to predict fire behavior before ignition. Although experience is the best teacher for predicting fire behavior, an understanding of several climatic, vegetative, and topographic factors is the first step.

12.6.1 Fuel and Weather

12.6.1.1 Fuel characteristics

Fire intensity is directly proportional to the amount of fuel surface area exposed to oxygen [5] and is generally greater with increased amounts of fuel. However, the arrangement and surface-to-volume ratio of fuels are important. When vertical fuels, such as standing grasses or pine needles draped over shrubs, are present, fuel surface area is much greater than if the same amount of fuel was lying on the ground. A fire in vertical fuels is hot and moves quickly. Moreover, the amount of fuel surface area is affected by the size of fuel particles. Large fuels, such as felled stems or branches, have small surface areas and produce cool fires that burn over long periods. Fine fuels, such as pine needles or grasses, have relatively large surface areas and burn quickly and intensely.

Fire intensity is also closely related to fuel moisture, whose effect on combustion can be described as a smothering of the fire [5]. For combustion to occur, enough water must be boiled out of fuels to allow oxygen buildup. Because energy is required to evaporate water, fires burning in moist fuels are cooler and spread more slowly than those in dry fuels. At 7 to 10% moisture content, fuel consumption will be nearly complete. Burning at slightly higher fuel moisture contents is often recommended to leave some fuels unburned, to help prevent erosion and nutrient loss. When fuel buildup is heavy, burning at high fuel-moisture contents is recommended to produce cool fires that will protect overstory crop trees. For most objectives, prescribed burning should be conducted when the moisture content of fine fuels is between 7 and 20% of dry weight [41].

Fine fuel moisture content is closely related to relative humidity. As relative humidity drops, evaporation increases rapidly, allowing oxygen to reach fuel particles. Fuels are usually too moist to burn when relative humidity is above 60%. In contrast, fine fuels are extremely dry when relative humidity is 20% or less, and burning becomes dangerous. For most objectives, prescribed burning should be conducted when relative humidity is between 30 and 50% [55].

12.6.1.2 Wind and temperature

Wind can influence fire behavior in several ways. Any air movement increases the supply of oxygen to fuels and, therefore, fire intensity. Wind also tilts flames, which affects the rate and direction of spread. When flames are tilted toward unburned fuels (head fires), the heat of the flame tip increases fuel drying and, therefore, the rate of spread. When flames are tilted away from unburned fuels (backing fires), wind disperses heat away from unburned fuels, causing flames to travel slowly. Some wind is beneficial when using either head or backing fires to disperse heat and, therefore, reduce damage to overstory trees. Without wind, heat rises directly over flames and may scorch crowns.

Acceptable wind speeds for prescribed burning range from 1 to 5 m/sec within a stand, or 2 to 9 m/sec 6 m above the ground in open areas. Backing fires can be used with wind speeds at the upper end of these ranges, but head fires should be limited to lower and moderate wind speeds. Winds should also be from a consistent direction to ensure predictable fire behavior. In the South, westerly or northwesterly winds in a high pressure system following the passage of a winter cold front are most reliable; easterly winds are unreliable except in coastal areas [41].

Ambient temperature partially determines the amount of vegetation killed by any prescribed fire. Summer fires kill vegetation more readily than winter fires because less heat is required to raise temperatures to lethal levels. To protect overstory trees from excessive scorch, burning at relatively cool temperatures, –10 to 10°C, is recommended. Temperature also affects relative humidity and fuel moisture. As afternoon temperatures rise, the air holds more moisture and relative humidity drops. Therefore, relative humidity should be monitored throughout a prescribed burn to ensure that burning stays within recommended guidelines.

12.6.2 Firing Methods

The choice of firing method is an important step in predicting fire behavior and achieving management objectives. Under a given set of fuel, weather, and topographic conditions, fire intensity can range from low to high depending on the firing method chosen. A fire manager must not only carefully select a technique to fit prevalent burning conditions but also remain flexible to alter the chosen technique if conditions change.

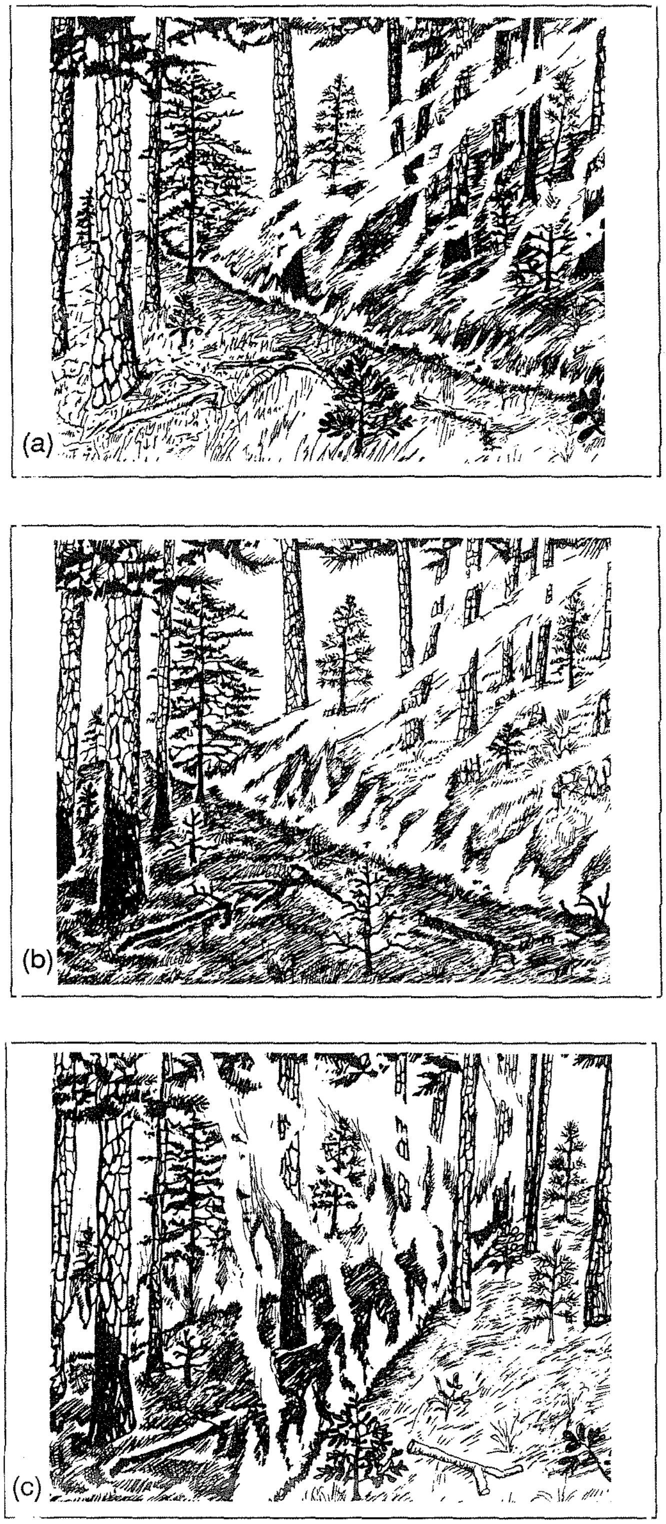

Figure 12.6. Firing methods: (a) backing fire, (b) head fire, and (c) flanking fire.

Fires follow any of three general patterns. Backing fires move into the wind or downslope, are typically cool, and travel slowly (Fig 12.6a). Head fires move with the wind, are typically hot, and travel quickly (Fig. 12.6b). Flanking

Figure 12.7. The strip-head fire technique.

Figure 12.8. The ring fire technique.

fires move perpendicular to the wind and are moderately hot (Fig 12.6c). Every firing method available to managers produces one of these patterns or any combination of the three. Firing methods discussed by Mobley at al. [41] and Brown and Davis [5] are summarized here.

12.6.2.1 Backfire

The backfire technique uses a series of parallel backing fires, each moving into the wind or downslope. Fire lines are prepared around the boundaries of the burn unit and through its interior at right angles to prevailing winds or along the contour of a slope. Interior fire lines should be parallel and approximately 200 to 400 m apart. The first backing fire set should be on the leeward side of the burn unit or along the ridge; subsequent strips of fire are set in order, from leeward to windward or downslope.

The backfire technique produces the least intense fire of any firing method, moving approximately 20 to 60 m/hour and causing little crown scorch. It is the safest technique, particularly in heavy fuels. However, backing fires are expensive because they travel slowly and require interior fire lines. Strong winds are desirable to dissipate smoke but have little effect on the rate of spread. This technique is best suited to areas where fuel loading is high, summer burning, or young stands where crown damage is likely.

12.6.2.2 Strip-head fire

The strip-head fire technique uses a combination of backing and head fires to burn an area quickly (Fig. 12.7). It produces a relatively intense fire and, therefore, should be limited to stands with medium to tall trees or to open areas. Fire lines are required around the boundaries of the burn unit but not within it.

At first, a backing fire is set on the leeward side or along the ridge of the unit. After the backing fire effectively widens a fire break (the combination of fire line and burned land), a second strip of fire is set parallel to the first approximately 20 to 60 m upwind or downslope. Because there are no interior fire lines, the second fire strip splits into a head fire moving toward the backing fire set earlier and a second backing fire. As the head fire meets the first backing fire, heat from the two combine, greatly increasing fire intensity for a short period. After the fires burn out, a third strip is set ahead of the second backing fire. The process is then repeated until the entire unit has been burned.

The strip-head fire technique has several advantages. It is less expensive than backing fires because interior fire lines are unnecessary and less time is required. The method is flexible because the direction of fire strips can be altered to adjust for variations in wind direction. Since it produces a higher intensity fire, it can be used under marginal conditions (such as high relative humidity and fuel moisture or low temperature and wind speed) or in flat fuels (such as hardwood leaves).

Care should be taken, however, to prevent scorching caused by high fire intensity when backing and head fires meet. Burning at low ambient temperatures is recommended, as is limiting the distance between strips. Because head fires build in intensity as they move through a stand, excessive heat buildup is avoided when the distance between fire strips is small. However, short distances between strips also should be avoided because of increased cost of labor and time required to burn an area; moreover, if the distance between fire strips is small, a large portion of the stand will be burned under the effect of two fires coming together and average fire intensity may be too high. The proper spacing between fire strips is best determined at the time of burning by experienced personnel who can judge by prevailing fuel and weather conditions.

12.6.2.3 Flank fire

As with all firing techniques, the flank fire technique begins with a backing fire to secure a fire break. Then, several fire strips are set into the wind or perpendicular to the backing fire. Each fire strip burns at approximately 45°

from the wind direction. Fire strips should be uniformly spaced and set at the same time. Therefore, good communication between crew members is essential.

The flank fire technique is most often used to supplement other burning techniques, particularly to speed backing fires. This technique is rarely used over large areas because considerable knowledge of fire behavior is required to produce uniform results. Any change in wind direction can quickly produce a head fire. Where lateral flanks meet, heavy turbulence and fire whirls can develop, causing excessive scorch. Flank fires are best used in medium to tall stands with light fuel buildup or in open areas.

12.6.2.4 Ring fire

The ring fire technique combines backing, head, and flanking fires. Fire lines are plowed around the burn unit and a backing fire is set on the leeward side to produce a fire break (Fig. 12.8). Once the fire break is secure, strips of fire are set around the perimeter of the entire unit. Since each fire strip moves away from the fire line, there is little chance that fire will cross fire lines. However, when several fire strips meet in the center of a unit, fire intensity is very high. Strong convection columns, which can carry flaming embers outside of the protected unit, often result.

The ring fire technique is best suited for open areas such as those about to be seeded or planted. Because of its typically high intensity, the ring fire is well suited for reducing logging residues. It can also be used in older stands when fuel buildup is light and weather conditions are marginal for burning; however, extreme caution is mandatory.

12.6.2.5 Spot fire

The spot fire technique is particularly useful for burning large areas quickly and is the most common technique for aerial ignition. Once a fire break is secured by a backing fire, spots of fire are set at a uniform distance along parallel lines (Fig. 12.9). Each spot acts as a backing, flanking, and head fire. When fires are lit by ground crews, spots are set on fire simultaneously along each line. When fires are aerially ignited, spots are set on fire along one flight line at a time. Both with ground crews and aerial ignition, the entire burn unit is set on fire quickly, resulting in numerous circular fires in a grid pattern.

The spot fire technique was first developed in Australia in areas where only 40 to 50% coverage by fire was desired. Fires were set when fuel moisture contents were high so that each spot did not influence the others and burned out before flames came together. The technique has been adapted to southern U.S. forests where complete fire coverage is desired. In such areas the distance between spots is critical for controlling fire intensity. If spots are widely spaced, individual spots can build up hot fire heads and create explosive conditions when flames meet. If spots are too close, fire junction zones will be numerous, increasing fire intensity. The proper distance between spots varies according to fuel and weather conditions but is generally 40 to 60 m. Because intensity is typically high with this technique, use of spot fires should be limited to medium to tall stands and open areas.

Figure 12.9. The spot fire technique.

12.6.3 Fire Intensity and Residence Time

The more heat produced by a prescribed fire, the more vegetation will be killed and the more fuel consumed. Most trees become more resistant to heat as they grow larger because of greater height and bark thickness. Therefore, hotter fires are required to kill larger vegetation. During prescribed burning, trees are killed either when enough heat is applied at the base of a stem to girdle the cambium or severely damage the root system or when fire intensity is relatively high and the heat rising above the fire becomes sufficient to scorch leaves and buds. However, southern pines are more likely to be killed from a combination of crown and stem damage than from either alone [17].

Lethal temperatures are determined not only by the amount of heat produced by prescribed fire, but also by the duration of exposure, or residence time [20]. Brown and Davis [5] define residence time as the time required for the forward spread of a flame front to travel a distance equivalent to the depth of that front. Plant tissue can be killed instantaneously at high temperatures but can also be killed at lower temperatures if residence time is increased. For example, Nelson [44] found that pine needles were killed when exposed both to 64°C for only 3 seconds and to 52°C for 11 minutes.

The combination of fire intensity and residence time must be considered when planning a prescribed fire for specific objectives. Backing fires produce relatively little heat but can have sufficient residence time to be lethal. Depending on the height of the vegetation, backing fires are more likely to damage stems and roots than crowns. Waldrop and Lloyd [71] observed mortality of young loblolly pines after a winter backing fire causing little or no crown damage. Strip-head fires are more likely to damage crowns than stems of older pines. Heat rising above flames is often sufficient to kill unprotected needles, but residence time is too short for heat to penetrate bark and reach lethal levels at the cambium.

12.6.4 Prescribed Burning on Slopes

Sloping terrain, which is common in the Piedmont and mountain regions of the Southeast, can complicate prescribed burning. Effects of slope on fire are similar in some ways to those of wind. A fire traveling up a steep slope resembles one being pushed by a steady wind. The hot tip of a flame is tilted toward unburned fuels, promoting fuel drying and increasing fire intensity. However, fires burning on level terrain produce an indraft caused by a convection column ahead of the fire. The indraft, which tends to slow head fires, does not occur on slopes. Fires traveling downslope resemble those backing into the wind. Flame tips are tilted away from unburned fuel, so drying is not as rapid and fire intensity remains low.

Wind patterns in sloping terrain must also be considered. As the Earth's surface warms during daylight hours, air rises, causing a prevailing daytime upslope wind in hilly terrain. Wind speed increases with elevation because greater volumes of air are moving upslope. The combination of slope effects and upslope winds will cause head fires to travel much more quickly than on flat terrain. Prevailing upslope winds are most common under clear skies and weak pressure gradients. Strong pressure systems create heavy winds that may completely offset convection effects [5].

Fuel moisture content varies by aspect in sloping terrain. Slopes with a southern exposure receive more radiation in the Northern Hemisphere than those with a northern aspect. Therefore, fuel drying is much slower on north-facing slopes and prescribed burning more difficult. In many cases, a backing fire can readily be used on the southern side of a mountain whose northern side cannot support even a head fire because fuel moisture content is too high.

12.6.5 Safety

Any prescribed fire can grow out of control and cause a wildfire. Precautions for preventing wildfires, as discussed earlier, include proper planning, preparation of the burn site, and execution of the fire. However, precautions should also be taken to ensure the safety of personnel working with the fire and that of the general public.

No burn should be conducted without experienced personnel. The fire boss must be familiar with the particular burning technique to be used and the burning conditions. The fire boss should explain to all personnel the organization of the crew, communication procedures, exact procedures for the chosen burning technique, and operation of all equipment. How to deal with unusually hazardous areas, such as those with heavy fuel loading, should be discussed, as should how to prevent crew fatigue and excessive exposure to smoke. Each crew member should wear protective clothing including a hard hat, leather boots, a long-sleeved shirt, loose-fitting cuffless trousers, and gloves.

The welfare of the general public is of major concern. Smoke-management procedures (see 12.3.3) should be strictly followed to prevent highway accidents and air pollution. If the burned area is readily accessible, the fire crew should be prepared to control traffic created by curious observers. Signs should be posted along roads warning of possible smoke hazards.

12.7 Conclusions and Recommendations

Prescribed fire is a versatile, cost-effective management tool in the regeneration of southern pines. Its frequent use throughout a rotation controls the size of shrub and hardwood understory, which makes site and seedbed preparation less expensive. Prescribed fire can be used either before or after logging, depending on season of harvest, to prepare seedbeds for natural regeneration. It can be used effectively alone, or in combination with other techniques, to prepare sites for artificial regeneration.

Properly planned and executed, prescribed fire has minimal adverse environmental or social effects. Many southern forest ecosystems actually seem to benefit from periodic low-intensity fires, as evidenced by improved habitat for numerous wildlife species and increased soil fertility of burned Coastal Plain sites. Because fire was a major environmental factor in molding southern forests, it is not surprising that these ecosystems are resilient to both frequent low-intensity and occasional high-intensity fires.

Much remains to be learned to fine-tune prescribed burning to attain precise management goals. Proper planning, and execution according to the plan, will help managers achieve the desired results with minimal adverse impacts. Numerous laws and ordinances governing the use of prescribed burning, most of which pertain to smoke management and wildfire prevention, are already in effect.

As with other management practices, prescribed fire can be misused. Practitioners must be aware of potential damage to forest resources, as well as the possibility of lawsuits from smoke-related accidents, if prescribed fires are not conducted properly. Improper or careless application of the practice will further restrict the use of this valuable tool – a loss that forestry can ill afford.

References

1. Abercrombie, J. A., Jr., and D. H. Sims. 1986. Fell and burn for low cost site preparation. Forest Farmer 46:14–17.
2. Baker, J. B., and W. E. Balmer. 1983. Loblolly pine. Pages 148–152 *In* Silvicultural Systems for the Major Forest Types of the United States (R.M. Burns, tech. compl.). U.S.D.A. Forest Serv., Washington, D.C. Agric. Handb. No. 445. 191 p.

3. Boyer, W. D., and D. W. Peterson. 1983. Longleaf pine. Pages 153–156 *In* Silvicultural Systems for the Major Forest Types of the United States (R.M. Burns, tech. compl.). U.S.D.A. Forest Serv., Washington, D.C. Agric. Handb. No. 445. 191 p.
4. Brender, E. V., and R. W. Cooper. 1968. Prescribed burning in Georgia's Piedmont loblolly pine stands. J. Forestry 66:31–36.
5. Brown, A. A., and K. P. Davis. 1973. Forest Fire Control and Use. 2nd ed. McGraw-Hill Book Co., New York. 686 p.
6. Burger, J. A. 1983. Physical impacts of harvesting and site preparation on soil. Pages 3–11 *In* Maintaining Forest Site Productivity Proc., 1st Regional Technical Conference, 62nd Annual Meeting of the Society of American Foresters. Jan. 27–28, Myrtle Beach, S.C. Society of American Foresters, Washington, D.C.
7. Chapman, H.H. 1926. Factors determining natural reproduction of longleaf pine on cutover lands in LaSalle Parish, Louisiana. Yale Univ. School of Forestry Bull. 16. 44 p.
8. Chi, C., D. Horn, R. Reznick, D. Zanders, R. Opferkuch, J. Myers, J. Pierovich, L. Lavadas, C. McMahon, R. Nelson, R. Johansen, and P. Ryan. 1979. Source assessment: prescribed burning, state of the art. U.S. Environmental Protection Agency Industrial Environment Res. Lab., Research Triangle Park, N.C. EPA–600/2–79–019h. 107 p.
9. Clewell, A. F. 1966. Natural history, cytology, and isolating mechanisms of the native American lespedezas. Tall Timbers Res. Sta. Bull. 6:1–39.
10. Conner, R. N. 1981. Fire and cavity nesters. Pages 61–65 *In* Prescribed Fire and Wildlife in Southern Forests – Proc. of a Symposium (G. W. Wood, ed.). The Belle W. Baruch Forest Sci. Institute of Clemson Univ., Georgetown, S.C. 170 p.
11. Cushwa, C. T., E. V. Brender, and R. W. Cooper. 1966. The response of herbaceous vegetation to prescribed burning. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Res. Note SE–53. 2 p.
12. Cushwa, C. T., M. Hopkins, and B. S. McGinnes. 1977. Soil movement in established gullies after a single prescribed burn in the South Carolina Piedmont. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Res. Note SE–153. 4 p.
13. Cushwa, C. T., and J. B. Reed. 1966. One prescribed burn and its effects on habitat of the Powhatan game management area. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Res. Note SE–171. 2 p.
14. DeBell, D. S. 1979. Future potential for use of symbiotic nitrogen fixation in forest management. Pages 451–466 *In Symbiotic Nitrogen Fixation in the Management of* Temperate Forests (J. C. Gordon, C. T. Wheeler, and D. A. Perry, eds.). Forest Res. Lab., Oregon State Univ., Corvallis.
15. Dieterich, J. H. 1971. Air quality aspects of prescribed burning. Pages 139–151 *In* Proc. Prescribed Burning Symposium. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. 160 p.
16. Douglass, J. E., and D. H. Van Lear. 1983. Effects of prescribed fire on water quality of ephemeral Piedmont streams. Forest Sci. 29:181–189.
17. Ferguson, E. R. 1955. Fire scorched trees – will they live or die? Pages 102–112 *In* Proc. 4th Annual Forestry Symposium. School of Forestry, Louisiana State Univ., Baton Rouge.
18. Ferguson, E. R. 1957. *Stem-kill and sprouting following* prescribed fires in a pine-hardwood stand in Texas. J. Forestry 55:426–429.
19. Hall, J. A. 1972. Forest fuels, prescribed fire, and air quality. U.S.D.A. Forest Serv., South. Forest Exp. Sta., New Orleans, La. Res. ap. SO–56. 11 p.
20. Hare, R. C. 1965. Contribution of bark to fire resistance of southern trees. J. Forestry 63:248–251.
21. Harlow, R. F., and D. H. Van Lear. 1981. Silvicultural effects on wildlife habitat in the South (an annotated bibliography) 1953–1979. Dep. of Forestry, Clemson Univ., Clemson, S.C. Tech. Pap. No. 14. 30 p. 22.
22. Harlow, R. F., and D. H. Van Lear. 1987. Silvicultural effects on wildlife habitat in the South (an annotated bibliography) 1980–1985. Dep. of Forestry, Clemson Univ., Clemson, S.C. Tech.Pap.No.17. 142 p.
23. Hauenstein, E. B., and W. C. Siegel. 1981. Air quality laws in southern states: effects on prescribed burning. South. J. Appl. Forestry 5(3):132–145.
24. Hilmon, J. B., and R. H. Hughes. 1965. Forest service research on the use of fire in livestock management in the South. Pages 261–275 *In* Proc. 4th Annual Tall Timbers Fire Ecology Conference. Tall Timbers Res. Sta., Tallahassee, Fla.
25. Johnson, A. S., and J. L. Landers. 1978. Fruit production in slash pine plantations in Georgia. J. Wildl. Manage. 42:606–613.
26. Jorgensen, J. W., and C. G. Wells. 1971. Apparent nitrogen fixation in soil influenced by prescribed burning. Soil Sci. Soc. Am. Proc. 35:806–810.
27. Kodama, H. E., and D. H. Van Lear. 1980. Prescribed burning and nutrient cycling relationships in young loblolly pine plantations. South. J. Appl. Forestry 4:838–841.
28. Komarek, E. V. 1974. Effects of fire on temperate forests and related ecosystems: southeastern United States. Pages 251–277 *In* Fire and Ecosystems (T.T. Kozlowski and C.E. Ahlgren, eds.). Academic Press, New York.
29. Langdon, O. G. 1971. Effects of prescribed burning on timber species in the southeastern Coastal Plain. Pages 34–44 *In* Proc. Prescribed Burning Symposium. April 14–16, Charleston, S.C. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. 160 p.
30. Langdon, O. G. 1981. Some effects of prescribed fire on understory vegetation in loblolly pine stands. Pages 143–153 *In* Prescribed Fire and Wildlife in Southern Forests – Proc. of a Symposium (G.W. Wood, ed.). The Belle W. Baruch Forest Sci. Institute of Clemson Univ., Georgetown, S.C. 170 p.
31. Lawson, E. R., and R. N. Kitchens. 1983. Shortleaf pine. Pages 157–161 *In* Silvicultural Systems for the Major Forest Types of the United States (R.M. Burns, tech. compl.). U.S.D.A. Forest Serv., Washington, D.C. Agric. Handb. No. 445. 191 p.
32. Lay, D. W. 1957. Browse quality and the effects of *prescribed burning in southern pine forests.* J. Forestry 55:342–347.
33. Lewis, C. E. 1964. Forage response to month of burning. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Res. Note SE–35. 4 p.
34. Lewis, C. E., and T. J. Harshbarger. 1976. Shrub and herbaceous vegetation after 20 years of prescribed burning in the South Carolina Coastal Plain. J. Range Manage. 29:13–18.
35. Lotti, T. 1961. The case for natural regeneration. Pages 16–23 *In* Proc. 19th Annual Forestry Symposium. Louisiana State Univ., Baton Rouge.
36. Lyon, L. J., S. C. Crawford, E. Czuhai, R. L. Fredrickson, R. F. Harlow, L. J. Metz, and H. A. Pearson. 1978. Effects of *fire on fauna.* U.S.D.A. Forest Serv., Washington, D.C. Gen. Tech. Rep. WO–6. 41 p.
37. McKee, W. H. 1982. Changes in soil fertility following prescribed burning on Coastal Plain pine sites. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Res. Pap. SE–234. 23 p.
38. McMahon, C. K. 1976. Effects of forest emissions on air

quality. Pages 75–82 *In* Proc. Fire by Prescription Symposium. U.S.D.A. Forest Serv., Atlanta, Ga. 127 p.
39. Metz, L. J., T. Lotti, and R. A. Klawitter. 1961. Some effects of prescribed burning on Coastal Plain forest soil. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Res. Pap. 133. 10 p.
40. Mobley, H. E. 1985. Smoke management. Pages 47–50 *In* Prescribed Fire and Smoke Management in the South: Conference Proc. (D.D. Wade, compl.). Sept. 12–14, 1984, Atlanta, Ga. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. 194 p.
41. Mobley, H. E., R. S. Jackson, W. E. Balmer, W. E. Ruziska, and W. A. Hough. 1978. A guide for prescribed fire in southern forests. U.S.D.A. Forest Serv., Southeast Area, State and Private Forestry, Atlanta, Ga. 40 p.
42. Moehring, D. M., C. X. Grano, and J. R. Bassett. 1966. Properties of forested loess soils after repeated prescribed fires. U.S.D.A. Forest Serv., South. Forest Exp. Sta., New Orleans, La. Res. Note SO–40. 4 p.
43. Morris, L. A., W. L. Pritchett, and B. F. Swindel. 1983. Displacement of nutrients into windrows during site preparation of a flatwood forest soil. Soil Sci. Soc. Am. J. 47:591–594.
44. Nelson, R. M. 1952. Observations on heat tolerance of southern pine needles. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Sta. Pap. No. 14. 6 p.
45. Nelson, R. M., I. H. Sims, and M. S. Abell. 1933. Basal fire wounds on some southern Appalachian hardwoods. J. Forestry 31:829–837.
46. Outcalt, K. W., and W. E. Balmer. 1983. Sand pine. Pages 170–171 *In* Silvicultural Systems for Major Forest Types of the United States (R.M. Burns, tech.compl.). U.S.D.A. Forest Serv., Washington, D.C. Agric. Handb. No. 445. 191 p.
47. Phillips, D. R., and J. A. Abercrombie, Jr. 1987. Pine-hardwood mixtures – a new concept in regeneration. South. J. Appl. Forestry 11(4):192–197.
48. Phillips, D. R., and D. H. Van Lear. 1984. Biomass removal and nutrient drain as affected by whole-tree harvest in southern pine and hardwood stands. J. Forestry 82:547–550.
49. Pyne, S. J. 1982. Fire in America. Princeton Univ. Press, Princeton, N.J. 654 p.
50. Richter, D. D., C. W. Ralston, and W. H. Harms. 1982. Prescribed fire: effects on water quality and forest nutrient cycling. Science 215:661–663.
51. Sandberg, D. V., J. M. Pierovich, D. G. Fox, and E. W. Ross. 1978. Effects of fire on air. U.S.D.A. Forest Serv., Washington, D.C. Gen. Tech. Rep. WO–9. 40 p.
52. Sanders, B. M., and D. H. Van Lear. 1987. Pre- and post-burn photo series for pine-hardwood logging slash in the Southern Appalachians. Pages 41–48 *In* Proc. 9th Conference on Fire and Forest Meteorology. April 21–24, 1987, San Diego, Calif.
53. Schock, P., and D. Binkley. 1986. Prescribed burning increased nitrogen availability in a mature loblolly pine stand. Forest Ecol. Manage. 14:13–22.
54. Shearin, A. T., M. H. Bruner, and N. B. Goebel. 1972. Prescribed burning stimulates natural regeneration of yellow poplar. J. Forestry 70:482–484.
55. Shepherd, J. G. 1985. Weather, fire danger rating systems, and fire behavior use in prescribed burning and smoke management in the South. Pages 51–56 *In* Prescribed Fire and Smoke Management in the South: Conference Proc. (D.D. Wade, compl.). Sept. 12–14, 1984, Atlanta, Ga. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. 194 p.
56. Shoulders, E., and G. Parham. 1983. Slash pine. Pages 162–166 *In* Silvicultural Systems for the Major Forest Types of the United States (R.M. Burns, tech. compl.). U.S.D.A. Forest Serv., Washington, D.C. Agric. Handb. No. 445. 191 p.
57. Siegel, W. C. 1985. Legal implications of prescribed burning in the South. Pages 77–86 *In* Prescribed Fire and Smoke Management in the South: Conference Proc. (D.D. Wade, compl.). Sept. 12–14, 1984, Atlanta, Ga. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. 194 p.
58. Stoddard, H. L. 1931. The Bobwhite Quail: Its Habits, Preservation and Increase. Scribner's, New York. 559 p.
59. Stransky, J. J., and L. K. Halls. 1980. Fruiting of woody plants affected by site preparation and prior land use. J. Wildl. Manage. 44:258–263.
60. Stransky, J. J., and R. F. Harlow. 1981. Effects of fire in the Southeast on deer habitat. Pages 135–142 *In* Prescribed Fire and Wildlife in Southern Forests – Proc. of a Symposium (G.W. Wood, ed.). The Belle W. Baruch Forest Sci. Institute of Clemson Univ., Georgetown, S.C. 170 p.
61. Swank, W. T., and J. E. Douglass. 1977. Nutrient budgets for undisturbed and manipulated hardwood forest ecosystems in the mountains of North Carolina. Pages 343–364 *In* Watershed Research in Eastern North America: A Workshop to Compare Results, Vol. 1 (D.L. Correll, ed.). Chesapeake Bay Center for Environmental Studies, Edgewater, Md.
62. Tiedemann, A. R., C. E. Conrad, J. H. Dieterich, J. W. Hornbeck, W. F. Megahan, L. A. Viereck, and D. D. Wade. 1979. Effects of fire on water. U.S.D.A. Forest Serv., Washington D.C. Gen. Tech. Rep. WO–10. 28 p.
63. Ursic, S. J. 1970. Hydrologic effects of prescribed burning and deadening upland hardwoods in northern Mississippi. U.S.D.A. Forest Serv., South. Forest Exp. Sta., New Orleans, La. Res. Pap. SO–54.
64. U.S.D.A. Forest Service. 1976. Southern forestry smoke management guidebook. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Gen. Tech. Rep. SE–10. 140 p.
65. U.S. Fish and Wildlife Service. 1984. Red-cockaded woodpecker recovery plan: agency review draft. Washington, D.C. 66 p.
66. Vance, E. D., and G. S. Henderson. 1984. Soil nitrogen availability following long-term burning in an oak-hickory forest. Soil Sci. Soc. Am. J. 48:184–190.
67. Van Lear, D. H., and S. J. Danielovich. 1988. Soil erosion after broadcast burning in the southern Appalachians. South. J. Appl. Forestry 12(1):49–53.
68. Van Lear, D. H., J. E. Douglass, S. K. Cox, M. K. Augspurger, and S. K. Nodine. 1983a. Regeneration of loblolly pine plantations in the Piedmont by clearcutting with seed in place. Pages 87–93 *In* Proc. 2nd Biennial Southern Silvicultural Research Conference (E.P. Jones, Jr., ed.). Nov. 4–5, 1982, Atlanta, Ga. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Gen. Tech. Rep. SE–24. 514 p.
69. Van Lear, D. H., W. T. Swank, J. E. Douglass, and J. B. Waide. 1983b. Effects of two harvesting practices on the nutrient status of a loblolly pine plantation. Pages 252–258 *In* Proc. Symposium on Forest Site and Continuous Productivity (R. Ballard and S.P. Gessel, eds.). IUFRO Conference, Seattle, Wa. 406 p.
70. Wade, D. D. (compl.). 1985. Prescribed fire and smoke management in the South: conference Proceedings Sept. 12–14, 1984, Atlanta, Ga. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. 194 p.
71. Waldrop, T. A., and F. T. Lloyd. 1987. Precommercial thinning a sapling-sized loblolly pine stand with fire. South. J. Appl. Forestry 12(3):203–207.
72. Waldrop, T. A., and D. H. Van Lear. 1984. Effect of crown scorch on survival and growth of young loblolly pine. South. J. Appl. Forestry 8:35–40.

73. Waldrop, T. A., D. H. Van Lear, F. T. Lloyd, and W. R. Harms. 1987. Long-term studies of prescribed burning in loblolly pine forests of the southeastern Coastal Plain. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Gen. Tech. Rep. SE–45. 23 p.
74. Wells, C. G. 1971. Effects of prescribed burning on soil chemical properties and nutrient availability. Pages 86–97 *In* Prescribed Burning Symposium Proc. April 14–16, Charleston, S.C. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. 160 p.
75. Wells, C. G., R. E. Campbell, R. C. Froelich, and P. H. Dunn. 1979. Effects of fire on the soil. U.S.D.A. Forest Serv., Washington, D.C. Gen. Tech. Rep. WO–7. 34 p.
76. Wenger, K. L., and K. B. Trousdell. 1957. Natural regeneration of loblolly pine in the South Atlantic Coastal Plain. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Prod. Res. Rep. 13. 78 p.
77. Wood, G. W. (ed.). 1981. Prescribed fire and wildlife in southern forests-proceedings of a symposium. The Belle W. Baruch Forest Sci. Institute of Clemson Univ., Georgetown, S.C. 170 p.
78. Woods, F. W., H. C. Harin, and R. E. Caldwell. 1959. Monthly variations of carbohydrates and nitrogen in roots of sandhill oaks and wiregrass. Ecology 40:292–295.

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